The South Atlantic Current

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ABSTRACT

In this paper we use the historical hydrographic data base for the South Atlantic Ocean to investigate (i) the hydrographic boundary between the subtropical gyre and the Antarctic Circumpolar Current (ACC), the Subtropical Front (STF), and (ii) the southern current band of the gyre, which is called the South Atlantic Current (SAC). The STF begins in the west in the Brazil-Falkland (Malvinas) confluence zone, but at locations at and west of 45°W this front is often coincident with the Brazil Current front. East of 45°W the STF appears to be a distinct feature to at least the region south of Africa, whereupon it continues into the Indian Ocean. The associated current band of increased zonal speeds is the SAC, which, except for one instance, is found at or north of the surface STF until Indian Ocean water from the Agulhas retroflection is reached. A reversal of baroclinicity in the STF is observed south of a highly saline Agulhas ring, causing the SAC to separate from the STF and turn north into the Benguela Current. Zonal flow south of the STF is generally weak and serves to separate the South Atlantic and circumpolar currents. In the Argentine Basin, the SAC has a typical volume transport of 30 Sv (1 Sv = 10^6 m^3 s^{-1}) in the upper 1000 m relative to a deep potential density surface (σ_4 = 45.87 kg m^{-3}), and can be as high as 37 Sv. It is thus comparable to, or stronger than, the Brazil Current. In the Cape Basin, the transport of the SAC is reduced to about 15 Sv before it turns north to feed the Benguela Current. In late 1983 this flow was joined by about 8 Sv of water from the Agulhas Current.

1. Introduction

In the North Atlantic Ocean there exists a clearly defined closure to the upper-level circulation of the subtropical gyre. Such closure is less clear in the South Atlantic, which can be attributed, at least in part, to the comparatively small number of hydrographic surveys there and to the presence of the Antarctic Circumpolar Current (ACC). Between the latitudes of roughly 30° and 60°S, the South Atlantic is under the influence of strong northwesterly winds that drive a broad eastward drift, making it superficially difficult to distinguish between the southern current band of the subtropical gyre, which is weaker than its Gulf Stream-fueled counterpart in the North Atlantic, and the northern reaches of the ACC.

The hydrographic boundary between the South Atlantic subtropical gyre and the ACC has long been known as the Subtropical Convergence (Deacon 1933), a feature that Krümmel (1882) had already described as being a sharp temperature discontinuity stretching across most of the South Atlantic from the eddy-filled region where the Brazil and Falkland (Malvinas) currents meet. According to Deacon (1933, pp. 210 and 216), the convergence "is marked by a sudden change of surface temperature of at least 4°C, and a change of salinity of at least 0.50. Just north of the sub-tropical convergence the surface temperature varies from about 15.5°C in winter to 18.5°C in summer." In a more comprehensive paper, Deacon (1937, p. 72) stated, "The water just north of the convergence has a temperature of at least 11.5°C in winter and 14.5°C in summer, but where there is a strong southward movement the temperature may be as much as 5°C higher, . . . the salinity of the surface water is at least 34.9, and it may be as much as 35.5." It seems that the validity of these generalizations have been little questioned through the years, though Sverdrup et al. (1942) used a lower surface temperature of 10°C as demarcating the northern edge of subantarctic water. At the Greenwich meridian, Whitworth and Nowlin (1987) identified this boundary by a surface salinity gradient with salinities greater than 34.8 belonging to subtropical water.

Böhnecke (1936), among others, argued that the term used by Deacon (1933) ought to be reserved for a wind convergence at 30°–35°S, but there seems to be no evidence in the literature for such a feature. Instead, the supposed wind convergence may very well be Deacon's Subtropical Convergence as the line of maximum wind stress curl across the South Atlantic, and therefore maximum convergence due to wind, is near 40°S in the annual mean (Peterson and Stramma 1990). Deacon's use of the term Subtropical Conver-

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gence has been widely used for more than a half century, but recently the term Subtropical Front (STF), which we adopt, has come into use for the subtropical gyre–ACC boundary (Hofmann 1985; Whitworth and Nowlin 1987). The term Subantarctic Front (SAF) has also been used for this boundary in the western South Atlantic (McCartney 1977; Roden 1986, 1989; Olson et al. 1988), but as Peterson and Whitworth (1989) detailed, the SAF is much more commonly thought of as being the northernmost front within the ACC system.

The formation of the STF in the western South Atlantic has been scarcely documented. Flowing northward with the Falkland (Malvinas) Current along the Patagonian shelf are two types of upper-level water belonging to the ACC: Subantarctic Zone (SAZ) surface water and Polar Frontal Zone (PFZ) water. These two are separated by the Subantarctic Front. Peterson and Whitworth (1989) found that after it leaves the northern Drake Passage, the SAF turns north to become a part of the Falkland Current and remains a part of the current to at least 40°S, the region of the Brazil–Falkland confluence zone. There it retroflects back toward the south and finally turns east in the vicinity of 48°–49°S, just north of the Falkland Escarpment. Piola and Gordon (1989) also found the thermohaline structure across the Falkland Current to be similar to the zonation of the ACC in northern Drake Passage. The water of the Falkland Current, which comes into direct contact with the Brazil Current, is therefore that of the ACC's Subantarctic Zone (SAZ). A great deal of turbulent mixing takes place in the confluence zone, with the near-surface waters being further modified by admixture of river plume water from Rio de la Plata and by local air–sea interactions. The complexity of the upper-level thermohaline fields in the confluence zone has been described by Gordon (1981, 1989), Gordon and Greengrove (1986), and Peterson and Whitworth (1989).

Using satellite IR imagery, Olson et al. (1988) observed that the points at which the Brazil and Falkland currents separate from the western boundary (1000 m isobath) are usually not coincident, but that a zone up to 300 km wide populated with eddies resides between them and can be traced as a continuous feature into the ocean interior. Their nominal indicator for the seaward extension of Falkland Current water was taken to be the 16°C isotherm, a temperature considerably higher than any of the SAZ water flowing through Drake Passage, which in summer has maximum temperatures in the range of 8°–10°C (Sievers and Emery 1978; Sievers and Nowlin 1984). The SAZ water on the Patagonian Shelf warms as it flows northward, attaining temperatures on the order of 14°–16°C during summer (see for example Fig. 1 in Gordon and Greengrove 1986). The value of 16°C used by Olson et al. (1988) to trace the seaward extension of the Falkland Current is thus representative of the warmest SAZ water advected into the confluence zone and is a close indicator of the STF (a feature they called the Subantarctic Front). Away from the western boundary, Roden (1986) found the STF (also using the term Subantarctic Front) at 41°S, 40°–42°W in the austral spring to be distinct from a surface front farther north bounding Brazil Current water. At the surface, the STF, which he considered to be a branch of the ACC, was found to lie within the temperature and salinity ranges of 10°–13°C and 34.4–35.2‰, consistent with long-standing indicators. But because there are no subtropical waters within Drake Passage, the STF can not be a part of the circumpolar current.

Another surface temperature front in the southern Argentine Basin has been described by Ikeda et al. (1989). On the basis of several north–south XBT (expendable bathythermograph) sections made near the western boundary during summer, they found this front to be closely pinned to the Falkland Escarpment, much in the same place as where Peterson and Whitworth (1989) found the underlying SAF. The front described by Ikeda et al. (1989), the Falkland Escarpment front, is characterized by temperatures of 10°–12°C at 30-m depth, colder than what is associated with the STF during summer, but warmer than the 8°–10°C surface water coming through northern Drake Passage. Whether the surface front observed by Ikeda et al. (1989) is a permanent feature bounding the southern end of the eddy field coming from the confluence zone, south of the newly-forming STF, or whether it is a seasonal one is not clear.

The surface current associated with the STF is not particularly strong when compared with, for example, those associated with the fronts within the ACC. The intense surface temperature and salinity gradients at the STF tend to compensate one another in terms of density as warm and saline water lies to the north of cooler and fresher water (Roden 1986; Whitworth and Nowlin 1987). Roden (1986) reported surface speeds associated with the STF as being on the order of 20 cm s^{-1} relative to 1500 db in the Argentine Basin, while at the Greenwich meridian a surface velocity of 13 cm s^{-1} relative to the bottom has been observed (Whitworth and Nowlin 1987). From trajectories of surface drifters deployed during the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE), trajectories which reflect not only geostrophic flow but Ekman and Stokes contributions as well (Peterson 1985), surface speeds at the STF are about 26 cm s^{-1} (Hofmann 1985).

Basin-scale descriptions of the current associated with the STF and of how it closes the gyre circulation have been remarkably sparse. It would seem that little substantial knowledge has been added since Deacon's (1933, pg. 217) description:

> "Between 38° and 30°S subtropical water moves eastwards under the influence of westerly winds, and the

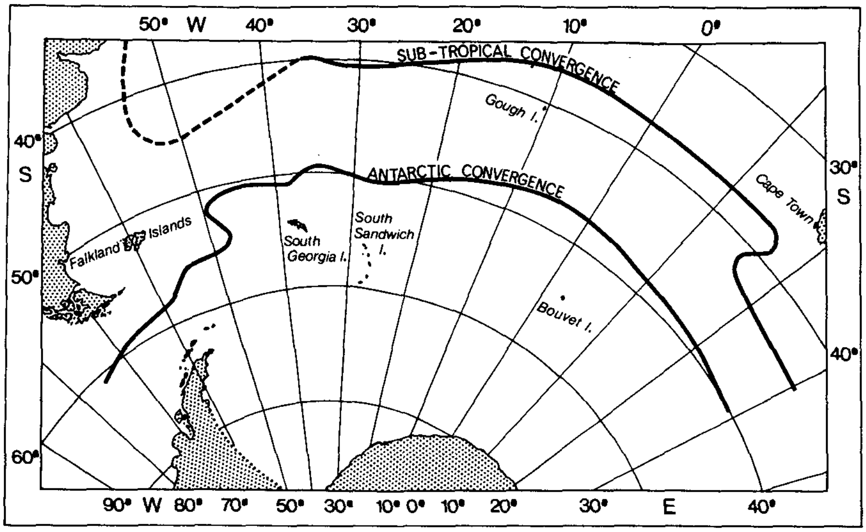

FIG. 1. The Subtropical Convergence (Subtropical Front) and Antarctic Convergence (Polar Front) in the South Atlantic Ocean (after Deacon 1933).

discontinuity slopes downward towards the north. The easterly movement carries water across the Atlantic Ocean from the Brazil Current towards Africa. Some of this water flows south of the Cape of Good Hope, joins water which is turned back from the Agulhas Current and flows eastwards across the Indian Ocean. The remainder turns northwards, joins the Benguela Current and flows north and east along the west coast of Africa."

Deacon's southern boundary to the subtropical water is shown in Fig. 1. In it, the STF begins in the Brazil–Falkland confluence zone and crosses the South Atlantic near 40°S before turning south near southern Africa to continue into the Indian Ocean. That the front continues into the Indian Ocean has been verified by Clowes (1950) who found it bending to the south near 37°S, 9°E before proceeding eastward and by Lutjeharms and Valentine (1984) who found it to lie at an average latitude of 41.7°S south of Africa. If the zonal current of the subtropical gyre follows the same route, then large quantities of subtropical water from the Atlantic would presumably flow into the Indian Ocean, which, as we will show, is not the case.

In this paper, we use hydrographic measurements from a number of cruises to first look into the origins of the STF in the western South Atlantic, and then to investigate the course of the front across the South Atlantic and to compute the zonal velocities and transports of the associated current. This zonal current is distinct from the ACC and closes the upper-level circulation of the subtropical gyre in the south; it is analogous to the open-ocean extension of the Gulf Stream [the North Atlantic Current (e.g. Krauss 1986)], and has been called the South Atlantic Current (McCartney 1977), a term which we adopt.

2. Methods

In the following, the STF is identified on the basis of maximum near-surface temperature and salinity gradients loosely following Deacon (1933, 1937). In cases where the salinity and temperature fronts are not coincidental, the more conservative salinity signature is used.

For geostrophic computations, a variable reference depth based on water mass properties is assumed. Away from the western boundary, the Antarctic Intermediate Water (AAIW) appears to circulate with the anticyclonic subtropical gyre (Buscaglia 1971; Reid et al. 1977), as do the deeper waters above 3500-m depth in the western South Atlantic (Reid et al. 1977). At the western boundary such is not the case; a thick layer of Circumpolar Deep Water (CDW) flows northward from the Scotia Sea, over the Falkland Plateau, and into the far southwestern Argentine Basin where it overrides abyssal water also moving in the same direction. These deep and abyssal waters flow northward along the Patagonian shelf until the southward-moving North Atlantic Deep Water (NADW) is encountered in the Brazil–Falkland confluence zone (Peterson and Whitworth 1989). Waters more dense than the NADW, the lower branch of CDW and the Weddell Sea Deep Water (WSDW), continue northward along the western boundary (Reid et al. 1977) while much of the remainder retroflects back toward the south inshore of the NADW and beneath the anticyclonic extension of the Brazil Current (Peterson and Whitworth 1989). The abyssal flow along the western boundary turns eastward at the Rio Grande Rise (~30°S) and then southward along the midocean ridge, describing a cyclonic circulation in the Argentine Basin (Reid et al. 1977; Georgi 1981) beneath the overlying anticyclonic flow. At the southern boundary of the Argentine Basin, the lower branch of CDW and the WSDW flow west as a deep western boundary current along the Falkland Escarpment while the NADW, the upper branch of CDW, the AAIW, and the surface water all move toward the east (Peterson and Whitworth 1989), consistent with the description of Reid et al. (1977).

The most appropriate reference level in the interior southwestern Atlantic, north of the bottom-reaching jets of the ACC (which we do not venture into), is therefore between the NADW and the lower branch of CDW. The potential density surface of $\sigma_4 = 45.87$ kg m^{-3} (or $\sigma_2 = 37.05$ kg m^{-3}) is used here. It generally lies in the depth range of 3000–3500 m and is computed using the IES-80 density equation. This value is almost identical to the $\sigma_4 = 45.92$ kg m^{-3} obtainable from the older equation. This reference layer should also give satisfactory results in the eastern basin. Stramma and Peterson (1989) used a reference layer lying just above the NADW (near $\sigma_2 = 36.9$ kg m^{-3}) at roughly 1500–2000 m to compute the transport of the Benguela Current north of 32°S, finding that the use of deeper references yielded only slightly different transport values. For a section by R/V *Knorr* at 1°E, Whitworth and Nowlin (1987) used the deepest common depths between stations as the ACC extends to the bottom, and observed the STF to be primarily a near surface feature with near-zero zonal velocities at depths greater than about 2400 m.

3. Observations

a. The STF in the Brazil–Falkland confluence zone

Shown in Fig. 2 is the horizontal distribution of salinity (from bottle samples) at 100-m depth in the southwestern Atlantic as compiled from the data reports of four different cruises: *Atlantis II* cruise 107 leg III (Guerrero et al. 1982), *Atlantis II* cruise 107 leg X (Piola et al. 1981), *Thomas Washington* Marathon Expedition leg 8 (Roden and Fredericks 1986), and *Robert D. Conrad* cruise 28-03 (Whitworth et al. 1988). Although the cruises were made at different times, no serious mismatches occur at the nonsynoptic joints of the field; in fact, the agreement seems remarkably good. Also shown in the figure are the positions of the SAF and the Polar Front (PF) as determined by Peterson and Whitworth (1989) from additional data contained in the same reports. As illustrated, there are practically no changes in salt content at the 100-m level within the PFZ. However, seaward of the return branch of the SAF there are intense horizontal gradients of salinity which are accompanied by a great deal of mixing. In the north, the core of the Brazil Current is marked by very high salinities (>36) near the continental shelf. South of 38°S the current separates from the western boundary and loses salt to the SAZ water moving south with the return flow of the Falkland Current. This mixing continues to approximately 46°S, whereupon the flow of subtropical water executes a large anticyclonic return to the north. It appears that at this depth the equatorward return is closing back on its source flow near 42°S, and is thus acting to supply additional low-salinity subantarctic water into the poleward lobe of subtropical water. The lobe itself might be nearing the completion of pinching-off from the Brazil Current, in which case a pool of subtropical water would be released into the northern side of the ACC. A similar, but more diluted, feature is evident north of Ewing Bank.

In Fig. 2, the STF begins, by definition of it being the boundary between subtropical and subpolar water, somewhere on the continental shelf north of 38°S, consistent with the paths of the 16°C isotherm shown in Fig. 6 of Olson et al. (1988). The intense salinity gradients observed here suggest that no real distinction can be made between the STF and the Brazil Current Front (BCF) north of 42°S, but that near this latitude with the apparent pinching-off of the poleward lobe of subtropical water it might be considered that the STF continues south whereas the BCF turns east. But the two features appear to be coincident once again as the northward return branch of the STF crosses 42°S near 49°W around a pool of SAZ water. Another split is indicated shortly downstream, followed by yet another merging near 45°W. At 42°–40°W the two fronts are again distinct, as noted by Roden (1986). Perhaps this is the region where the STF finally gets organized. The STF is mainly zonal at about 41°S between the isohalines of 34.4 and 35.2, whereas the BCF meanders toward the northeast with the higher salt contents. The BCF might just be executing another northward meander before merging with the STF farther downstream, but that seems unlikely considering that a recirculation of subtropical water exists to the west of 35°W (Stramma 1989). It would thus seem that the STF does not completely retain its identity from the BCF once it is first attained, but instead goes through a complex organizational phase in a highly variable eddy field.

b. Course of the STF and transport of the SAC

Several quasi-synoptic hydrographic sections crossing the STF in the South Atlantic, plus two sections consisting of nonsynoptic stations, have been extracted from a digitized data base supplied by the World Oceanographic Data Center (WODC) in Washington, DC. We also use a section made by R/V *Meteor* in June and July 1925 (Wüst 1932). The sections used and the locations of the STF are presented in Fig. 3. Some basic details concerning the sections are provided in Table 1, together with the locations of the stations immediately north and south of the STF and their surface salinities and temperatures. For the most part, the

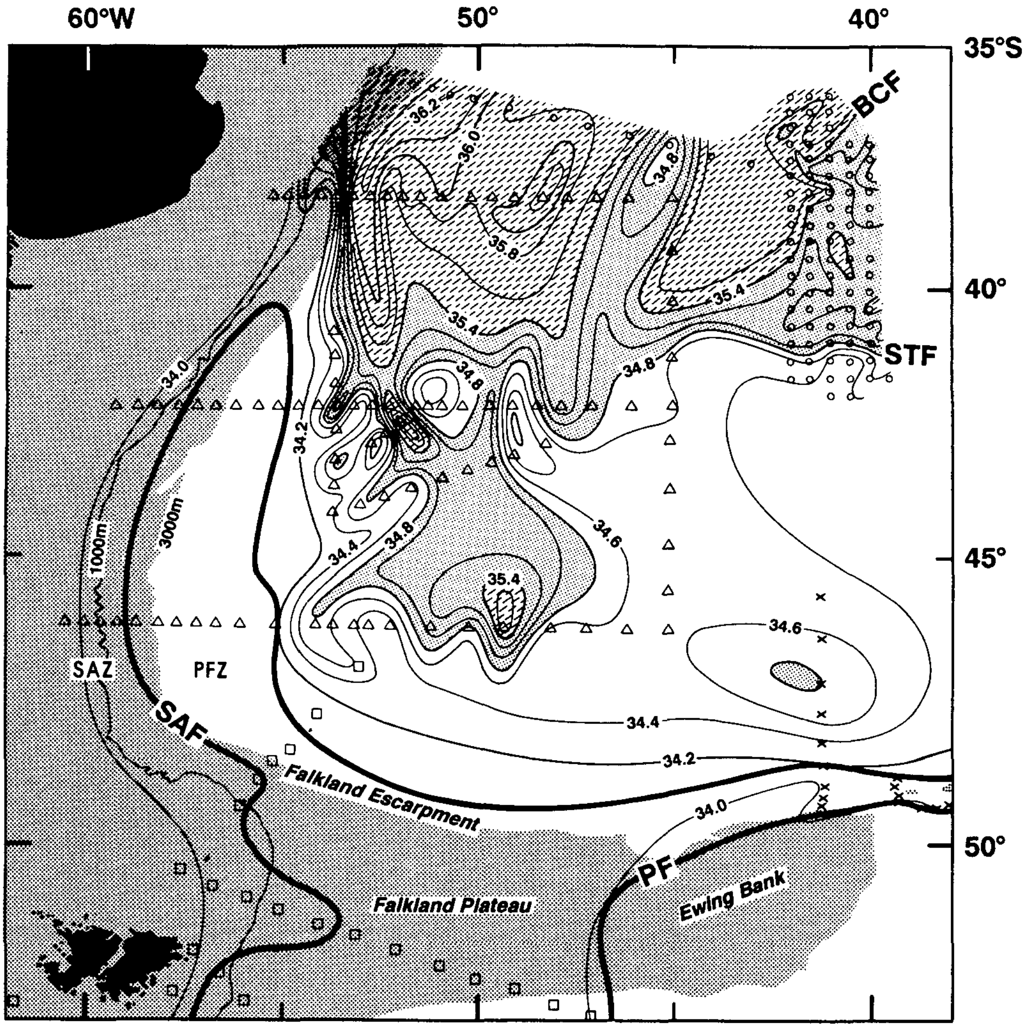

FIG. 2. Distribution of salinity at 100-m depth in the southwestern South Atlantic as constructed from bottle samples taken during the following four cruises: *Atlantis II* cruise 107 leg III (triangles); *Atlantis II* cruise 107 leg X (squares); *Thomas Washington* Marathon Expedition leg 8 (circles); and *Robert D. Conrad* cruise 28-03 (crosses). Indicated fronts are the Brazil Current Front (BCF), Subtropical Front (STF), Subantarctic Front (SAF), and Polar Front (PF), Also indicated are the Subantarctic Zone (SAZ) and the Polar Frontal Zone (PFZ). Positions of the SAF and PF are after Peterson and Whitworth (1989). Heavy shading denotes depths of 3000 m and less.

positions of the STF in Table 1 agree with those of Deacon's (1933) Subtropical Convergence (Fig. 1) and with his path based on the 34.9 isohaline (Deacon 1982): between about 35° and 25°W the front tends to be south of 40°S while it is north of that latitude between 25°W and 10°E. Referring again to Fig. 3, of the 17 *Meteor* stations shown south of 40°S, only 4 had surface salinities greater than 34.8. Two were in the west (41.7°S, 49.5°W and 41.4°S, 45.0°W), in the region of the southward extension and return of the Brazil Current. The other two were in the central South Atlantic (41.5°S, 23.2°W and 40.9°S, 14.2°W) where the STF is normally found north of 40°S during the austral summer. At 10° and 20°W, however, Lutjeharms (1985) observed the STF in the temperature field as being just south of 40°S. The two *Meteor* stations between 6° and 11°W had surface salinities of 34.4, which indicates that either the front was to their north or the samples were taken within eddies from the subantarctic zone. But this apparent latitudinal variability of the STF, combined with that depicted in Fig. 3 for the meridional sections in the west, is consistent with the fluctuations of 6° or more with possible seasonal variations noted by Deacon (1937, p. 59).

In the west, the R/V *Atlantis II* section (45°W) was used in the constructions of Fig. 2 and horizontal maps by Gordon (1981), Gordon and Greengrove (1986), and Peterson and Whitworth (1989). Shown in Fig. 4 are vertical distributions of temperature, salinity, oxygen, and eastward geostrophic velocity for this *Atlantis*

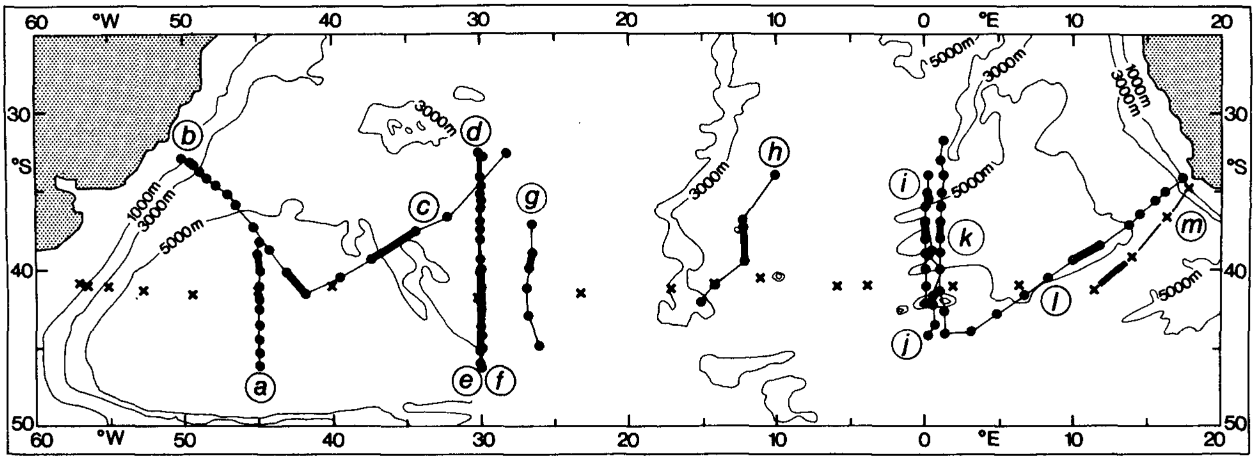

FIG. 3. Positions of hydrographic stations used except in the construction of Fig. 2. Letters correspond to cruises, which are given in tables 1 and 2. Crosses denote stations occupied by R/V *Meteor* in the year 1925. Heavy bars indicate positions of the Subtropical Front.

II section. A strong surface salinity gradient appears near 40°S, while the sharpest changes in surface temperature are south of 40°S. As noted earlier, the STF is not distinct from the BCF in this section. In the oxygen field, the contrasts between upper-level water masses is clear. North of 40°S is a lens of poorly-oxygenated (<5 ml l^{-1}) near-surface water typical of the subtropics, whereas to the south are oxygen-rich surface waters belonging to the SAZ. At depth, the cores of the various water masses above 4000 m can all be identified in the oxygen field. The oxygen maximum of AAIW lies at about 500-m depth south of the BCF–STF and deepens slightly to the north, while the oxygen-weak branches of CDW lie above and below the more highly-oxygenated NADW, which is centered near 2500-m depth. The freshest and most oxygenated AAIW lies beneath the subantarctic surface water to the south of the BCF–STF, but at greater depths the current seems to have little influence on the distributions of properties. In accordance with this are the geostrophic velocities, which are relatively meager with respect to those we observe near the STF at other locations. The highest surface velocities here are just under 10 cm s^{-1} (Table 2), which diminish to about 3 cm s^{-1} at 1000-m depth (Fig. 4). The comparative weakness of this current is partially due to the very strong near-surface salinity gradients acting in opposition to the temperature distribution, and to very weak flow normal to the section

TABLE 1. Sections appearing in Fig. 3 together with positions of the stations to the immediate north and south of the Subtropical Front (STF) and their surface salinities and temperatures. For locations near the STF, section (h) is composed of stations by the *Africana II* (Mar 1968) and *Discovery* (Feb 1926), while section (j) is composed of stations made in May and Sep 1936.

Ship	Longitude	Time	STF location (lat, °S)	Surface salinity	Surface temperature (°C)
(a) *Atlantis II*	45°W	Dec 1979	39.0–40.0, 45.0°W@	34.7–35.1	15.0–15.9*
(b) *Melville*	50°–42°W	Nov 1972	40.2–41.5, ~42°W	34.5–35.7	12.8–16.5+
(c) *Melville*	42°–28°W	Nov 1972	37.5–39.3, ~35°W	34.7–35.7	15.0–15.4*
(d) *Hudson*	30°W	Dec 1969	42.5–45.1, 30.0°W	34.4–35.0	10.2–13.5+
(e) *Vize*	30°W	May 1969	40.0–42.0, 30.0°W	34.7–35.1	12.6–14.6+
(f) *A. Shirshov*	29.9°W	May 1970	41.0–42.5, 29.9°W	34.7–35.0	11.0–12.9+
(g) *A. Kurchatov*	26.5°W	Nov 1971	38.9–39.7, 26.5°W	35.0–35.5	12.7–14.5
(h) (composite)	15°–10°W	Nonsynoptic	37.2–39.4, ~12°W	34.7–35.0	12.7–18.5
(i) *Vodyanitskii*	0°	Jan 1979	37.0–38.0, 0.0°	34.8–35.3	17.1–18.9*
(j) *Discovery*	0.5°E	Nonsynoptic	38.7–39.1, 0.5°E	34.6–35.0	13.1–12.3φ
(k) *Knorr*	1°E	Oct 1983	37.0–38.0, 1.0°E	34.7–35.2	12.3–14.1
(l) *Knorr*	1°–17°E	Nov 1983	38.5–39.5, ~10°E	34.5–35.2	11.0–13.7
(m) *Meteor*	11.5°–17°E	Jul 1925	39.2–41.2, ~13°E	34.4–35.1	10.3–13.9

@ STF not distinct from Brazil Current Front.
* Secondary temperature front to the south.
+ Secondary temperature and salinity fronts to the north.
φ Secondary temperature fronts to the north and south.

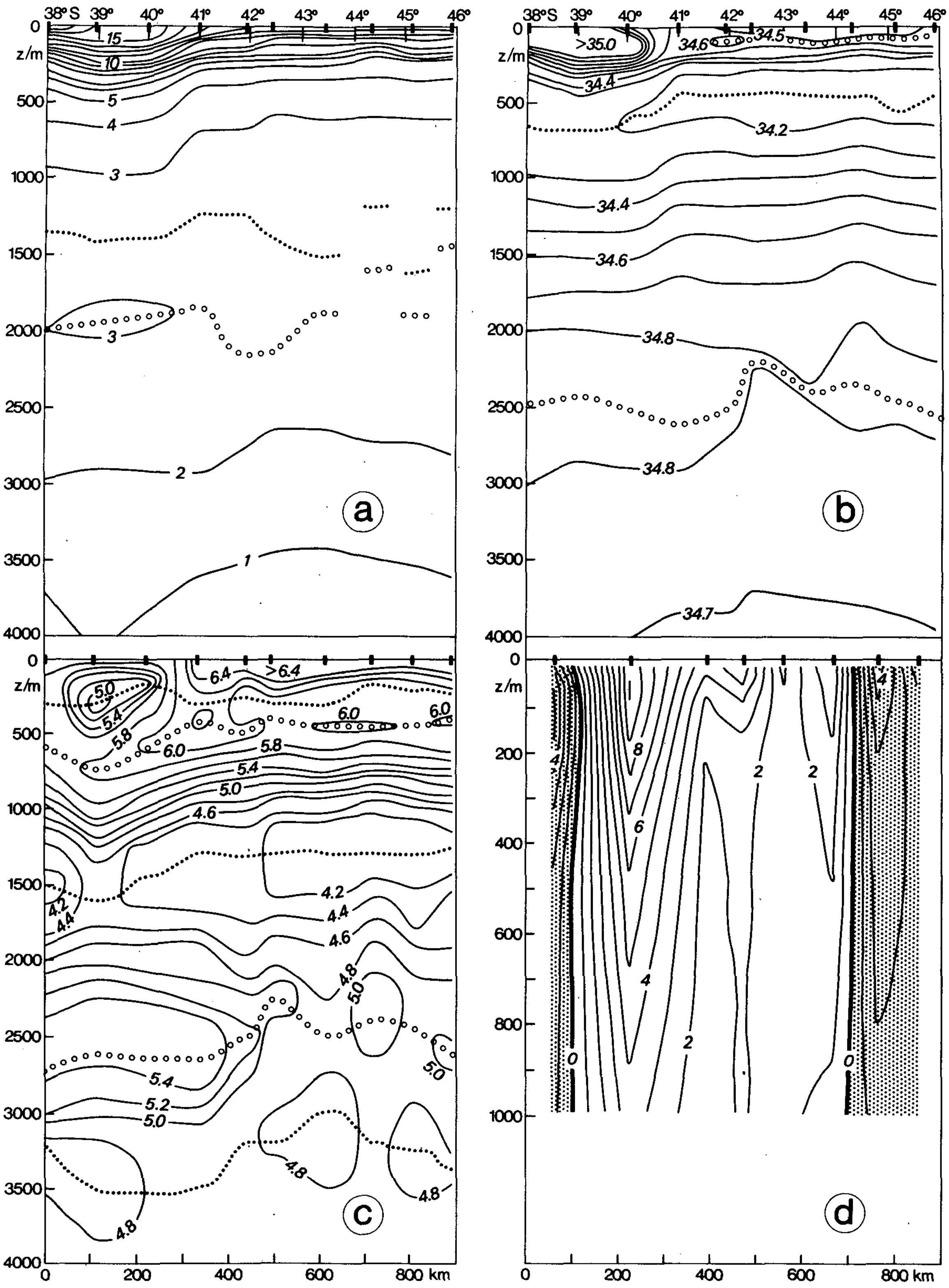

FIG. 4. Vertical distributions along the R/V *Atlantis II* section at 45°W of (a) temperature in °C, (b) salinity, (c) oxygen in ml l^{-1}, and (d) eastward geostrophic speed in cm s^{-1} (negative values shaded) relative to the potential density surface of $\sigma_4 = 45.87$ kg m^{-3} (2890–3120 m). Relative maxima are denoted by open circles, and relative minima by dots.

TABLE 2. Depths of the potential density surface of σ_4 = 45.87 kg m^{-3} used as reference for geostrophic calculations, together with maximum eastward geostrophic speeds at the surface for the South Atlantic Current (SAC) and eastward geostrophic transports (1 Sv ≡ 10^6 m^3 s^{-1}) in the upper 1000 m for the station pairs spanning the Subtropical Front (STF) in the sections shown in Fig. 3. Transport values for regions north of the STF are computed from the front northward to either the end of the particular section or until westward flow is encountered. The final column gives transport values for station pairs immediately south of the STF.

	Ship	Longitude	Reference depth (m)	Maximum velocity (cm s^{-1}) of SAC	Transports (Sv)		
					At STF	North of STF	South of STF
(a)	*Atlantis II*	45°W	2890–3120	9.8	14.1$^{@}$	−2.7	1.9
(b)	*Melville*	50°–42°W	3110–3320	27.0	29.9	−1.0	NA
(c)	*Melville*	42°–28°W	3050–3330	13.5	30.2	2.3	−6.1
(d)	*Hudson*	30°W	2940–3100$^+$	10.1	19.4	17.8	NA
(e)	*Vize*	30°W	2120$^+$–2170$^+$	12.8	12.5	16.0	5.7
(f)	*A. Shirshov*	29.9°W	2120$^+$–2290$^+$	9.0	4.0	15.6	3.2
(g)	*A. Kurchatov*	26.5°W	440$^+$–1980$^+$	NC	NC	NC	NC
(h)	(composite)	15°–10°W	200$^+$	NC	NC	NC	NC
(i)	*Vodyanitskii*	0°	510$^+$–1790$^+$	NC	NC	NC	NC
(j)	*Discovery*	0.5°E	3450–3480	7.4	2.3	11.7	−0.5
(k)	*Knorr*	1°E	3470–3560	13.8	8.8	−1.4	8.3*
(l)	*Knorr*	1°–17°E	3440–3570	—	−9.6	(eddies)	0.5
(m)	*Meteor*	11.5°–17°E	3320–3370	2.2$^{\phi}$	3.1$^{\phi}$	5.7$^{\phi}$	NA

$^{@}$ STF not distinct from Brazil Current Front.
$^+$ Deepest depth available.
* Two station pairs.
$^{\phi}$ 250–450 km station spacing.
NA: Not available.
NC: Not computed.

at greater depths which presumably is associated with the mesoscale activity evident in Fig. 2. The volume transport of this current is accordingly modest at 14.1 Sv in the upper 1000 m for the station pair spanning the frontal system.

In the diagonal NW–SE section made by R/V *Melville* (denoted as section b in Tables 1 and 2 and in Fig. 3), the STF is observed between the southernmost pair of stations slightly south of where it is in the *Washington* data in Fig. 2, and has an associated volume transport of nearly 30 Sv in the upper 1000 m. The vertical distributions of properties and geostrophic speeds (also relative to a layer between the NADW and the lower branch of CDW) along this *Melville* section appear in Figs. 4 and 13 of Reid et al. (1977). Two distinct northeastward current cores are evident, one being at the STF and the other being the Brazil Current return about 500 km to the northwest. The current at the STF is the stronger with speeds of about 27 cm s^{-1} at the surface and about 10 cm s^{-1} at 1000-m depth. The other diagonal (SW–NE) section made by the *Melville* (denoted as section c) in the same month yielded a comparably large transport for the SAC, but because the pair of stations spanning the STF were twice as far from one another as in the previous section, the surface speeds are much reduced. It appears that the intermediate and deep layers move more in the direction of the SAC than in the direction of the Brazil Current return, therefore it is preferable to have deep-reaching stations in the western basin for estimating transport rates. Using a shallower reference depth of about 1600 m according to Defant's (1941) level of no motion, Stramma (1989) obtained a reduced transport rate at the STF of 22 Sv in the upper 800 m for this same section. Accordingly, we make no attempt to calculate geostrophic transports with the *Washington* data shown in Fig. 2. The stations spanning the STF in that survey, for which we do not have the digitized records, reach to only 1500 db, a level where speeds at the front are still on the order of 5 cm s^{-1} (Reid et al. 1977).

The largest transport value for the SAC is found at the 30°W section by R/V *Hudson*. Combining the transport values at and north of the STF, the SAC carries approximately 37 Sv across that section (Table 2). Another section at 30°W, from the *Vize* yields 29 Sv. Both of these sections, and another at 30°W (from the *Shirshov*) show substantial, and in two cases, dominant transports occurring north of the STF. Based on only these three sections at 30°W, the STF appears to meander southward to the vicinity of 42° or 43°S while the SAC does not. The reason for this lies with shallow (<200 m deep) southward extensions of subtropical water overriding subantarctic surface water while part or most of the baroclinic structure associated with the STF remains in the north. In these three cases, a weaker, secondary surface front is observed some 200 to 300 km farther north and helps to account for the SAC being north of the main surface front. But this is not particularly new as Deacon (1933, p. 211) had already described shallow lenses of subtropical water overriding subantarctic water, and moreover, he (Deacon 1937, p. 57) even observed a southward displacement of the front (to 42°–43°S) at 30°W and noted that there were minor fluctuations extending 2°–3° farther north.

The hydrographic data base near 40°S between 25°W and the Greenwich meridian is extremely paltry; indeed, there are no synoptic meridional sections at all in the WODC files that cross the STF in this region, which is unfortunate because of the effects the midocean ridge might have on the transport of the SAC. In the western basin the deep waters move in the same general direction as the near-surface waters (Reid et al. 1977), whereas in the eastern basin there seems to be very little zonal flow at large depth beneath the STF (Whitworth and Nowlin 1987). Given similar baroclinic structures in the upper layers, the transport of the SAC should thus be less in the eastern basin than in the west, which we find to be the case. But the available data are too few to test whether there is a marked reduction as the current flows over the midocean ridge, or whether the flow gradually stems off to the interior of the subtropical gyre. The sections by the *Kurchatov* (26.5°W) and *Vodyanitskii* (0°) are useful for locating the STF, but the profiles are too shallow to yield meaningful transport values. The same is true of the section at 10°–15°W constructed from nonsynoptic stations, for which the deepest reference depth possible in the neighborhood of the front is just 200 m. Another nonsynoptic section is composed of stations made in five different years (in various seasons) near the Greenwich meridian during the 1930s from the *Discovery*. These stations all extend to depths greater than our reference at $\sigma_4 = 45.87$ kg m^{-3} and provide a volume transport of just 14 Sv (Table 2), with most of the transport occurring north of the STF. This transport value is just half that observed on average in the western basin, but because of the nonsynopticity of the section this value has to be regarded with caution. A quasi-synoptic section at 1°E by the *Knorr* (Ajax Cruise Leg 1) gives a similar transport of 17 Sv, but in that section nearly half the transport occurs in the two station pairs south of the front, which is anomalous.

Vertical fields of temperature, salinity, density, and geostrophic velocity for the *Knorr* section along 1°E in the vicinity of the STF are shown in Fig. 5. A clear surface salinity front is seen at 37°–38°S and is accompanied by a less pronounced surface temperature front. Southwards from the STF is a subsurface salinity maximum at 200–300 m depth, a feature that is often observed but seldom as conspicuously as in this section. A weak indication of such a tongue can be seen in the *Atlantis* section at 45°W in Fig. 4. Balances between diffusion and advection for similar subsurface salinity maxima south of New Zealand were investigated by Heath (1976). In this section near the Greenwich meridian, salinities greater than 34.8 are observed as far as 200 km south of the STF. This unusually strong subsurface extension is associated with secondary salinity and temperature fronts and a secondary current core between 39° and 40°S, approximately 200 km south of the primary surface fronts. The transport of the SAC is therefore not spread out to the north of the STF as is more common, but now substantial transports are found south of the front (Table 2). In this section the total transport of the SAC is 17 Sv in the upper 1000 m; nearly 9 Sv are associated with the primary surface front and 8 Sv occur in the 200-km wide band south of the front. Integrating the geostrophic flow of the SAC to the deepest common depth for this section (about 4700 m) yields a top-to-bottom transport of 23 Sv. Therefore, the vertical shear of the SAC at this location is strongly restricted to the upper kilometer. See Whitworth and Nowlin (1987) for descriptions of the currents and water masses farther south along this meridian based on observations made during the second leg of the *Knorr* Ajax cruise.

The first leg of the *Knorr* Ajax cruise was concluded with a diagonal line of stations ending about 500 km southwest of the Cape of Good Hope on November 5, 1983. The *Knorr* was then used in the Agulhas Retroflection Cruise (ARC) that began eight days later with a series of stations that can be used to complete the diagonal line made at the end of the Ajax Cruise Leg 1. However, several of the ARC stations were made to only about 1500-m depth, which we do not use. To complete the diagonal line, we use four bottom-reaching stations made during November 15–18. The resulting quasi-synoptic section is used for the vertical fields shown in Fig. 6. Proceeding from the north, a newly-shed ring from the Agulhas Current is crossed (described by Gordon et al. 1987; Lutjeharms and Gordon 1987). Our maximum surface velocity in the northern side of the ring is 38 cm s^{-1} relative to $\sigma_4 = 45.87$ kg m^{-3} ($\sim$3500 m), less than the 50 cm s^{-1} relative to 1500 db obtained by Gordon et al. (1987) with a shorter section along this line with better synopticity and closer station spacing. But our volume transport of 53 Sv in the upper 1000 m on the northern side of the ring is comparable to the 51 Sv relative to 1500 db obtained by Gordon et al. (1987), which is due to the Agulhas Current transport being largely confined to the upper 1000 m (Duncan 1970).

South of the ring, the STF is found between stations 57 and 58 (Fig. 6). An unexpected result is that the transport at the front, nearly 10 Sv, is now *northwestward,* which is independent of reference level and is in the opposite direction relative to the front as it had been in all our previous sections. This reversal of baroclinicity is evidently due to the near-surface salinity gradients being of such strength that they overcompensate the effects of temperature in the density field. The SAC is thus separated from the STF at this location and, as we will show, flows north into the Benguela Current. A different situation, though, existed in this

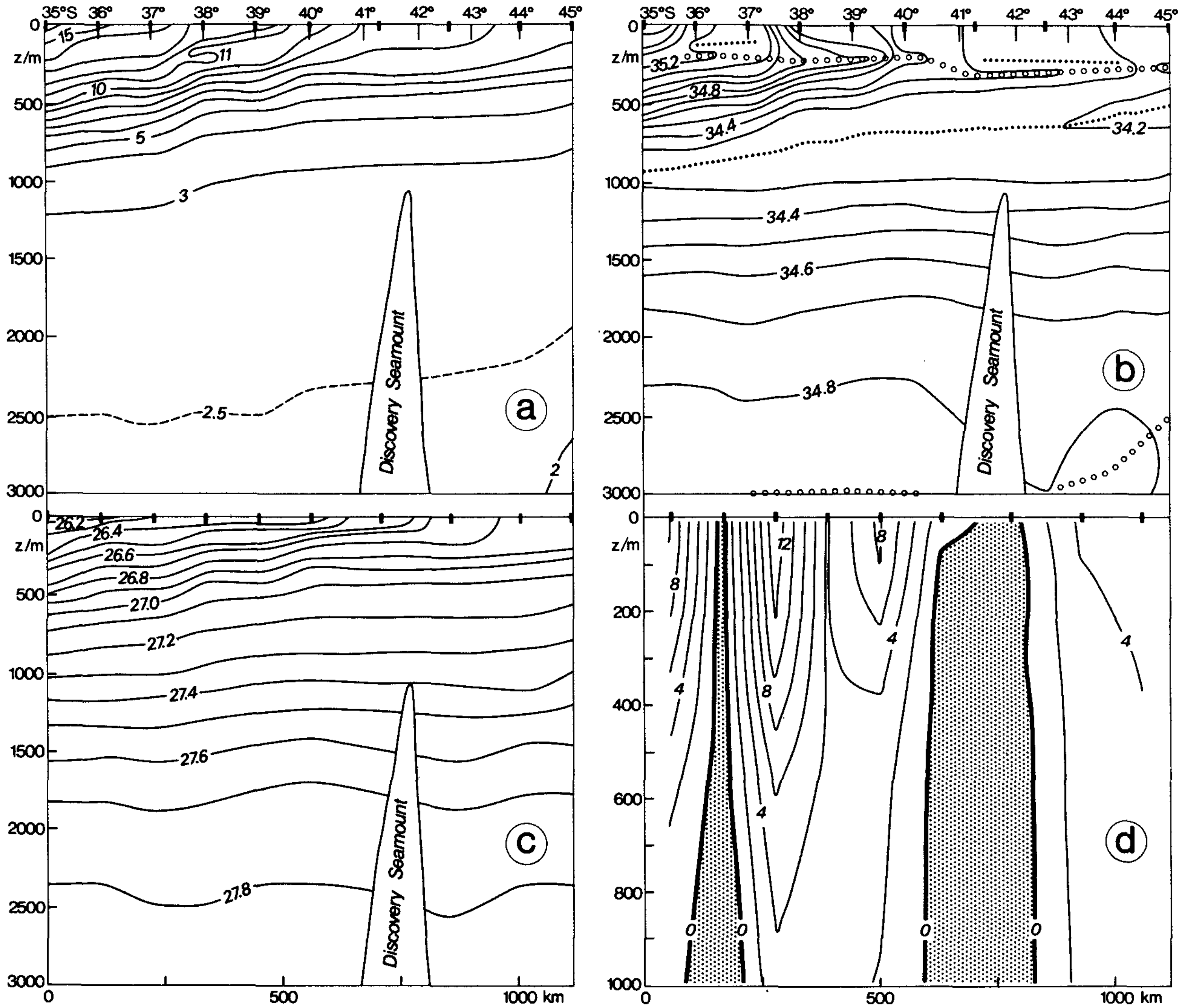

FIG. 5. Vertical distributions along the R/V *Knorr* section at 1°E of (a) temperature in °C, (b) salinity, (c) sigma-*t* in kg m^{-3}, and (d) eastward geostrophic speed in cm s^{-1} (negative values shaded) relative to the potential density surface of σ_4 = 45.87 kg m^{-3} (3470–3560 m). Relative maxima are denoted by open circles, and relative minima by dots.

region during July 1925. In the diagonal part of the R/V *Meteor* section from 41.2°S, 11.5°E to the South African coast (Fig. 3) the STF was located between 39.2°S and 41.2°S. There we find a weak transport of 3.1 Sv to the southeast with the station pair north of the front yielding a somewhat larger southeastward transport of 5.7 Sv. The total southeastward transport of 8.8 Sv at and north of the STF is smaller than our previous estimates for the SAC, and probably does not represent the entire current. These 8.8 Sv are compensated by a northwestward transport of 9.0 Sv (relative to, and above 690 m due to the shallowness of the coastal station) between the final station pair. It looks as though neither an Agulhas ring nor the Agulhas retroflection was sampled by the *Meteor* on this section, and thus there is no reversal of baroclinicity observed at the STF due to the presence of highly saline Indian Ocean Central Water to its north. The northwestward flow along the African coast was likely the return of the southeastward flow, back into the Atlantic after it had reached longitudes of the Agulhas retroflection. But because of the wide station spacing (250–450 km) and lack of supporting evidence in this region normally filled with eddies, we do not claim this to be the only plausible interpretation.

There is a net flow of 26 Sv in the upper 1000 m into the triangular region described by the two quasi-synoptic *Knorr* sections used here, which meet near the Greenwich meridian and 44°S (Fig. 3). A balancing flow of 26 Sv must proceed north out of the region. For comparison, the eastern portion of the zonal section made by the *Atlantis* along 32.5°S during the In-

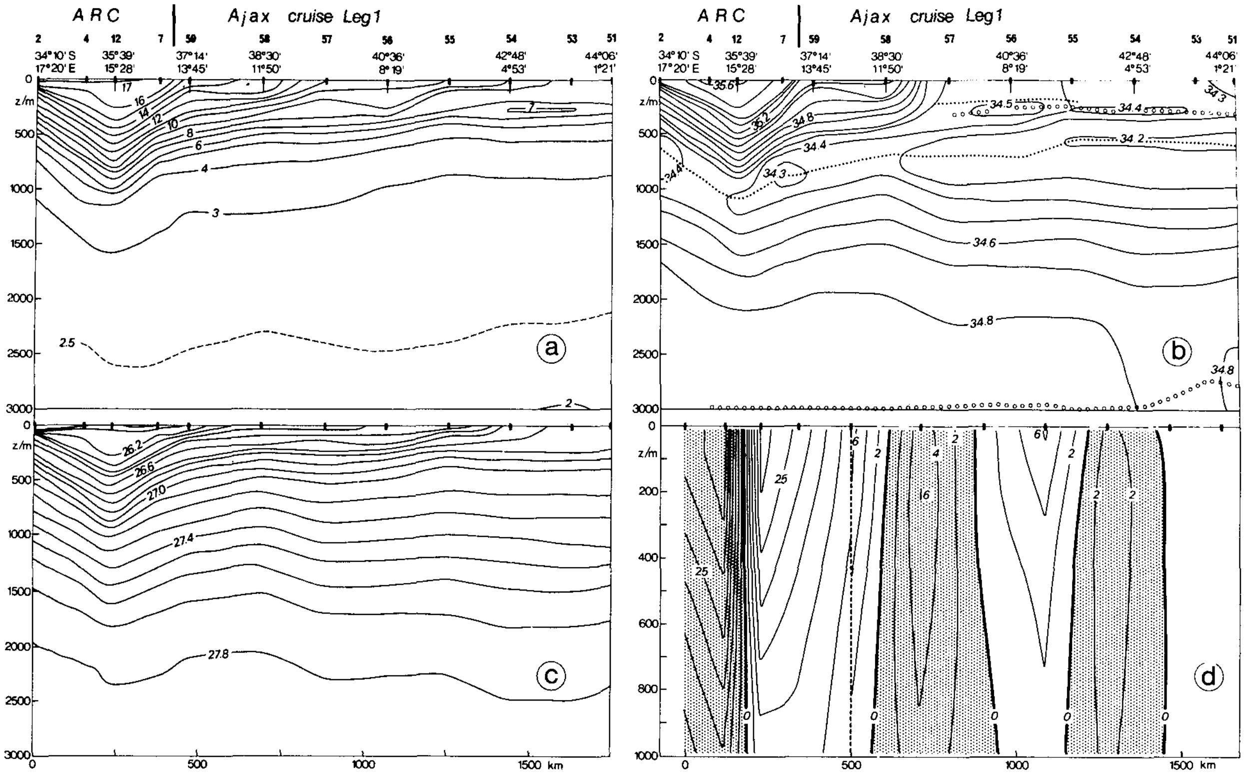

FIG. 6. Vertical distributions along a diagonal line of stations occupied by R/V *Knorr* in November 1983 between 1° and 17°E: (a) temperature in °C, (b) salinity, (c) sigma-*t* in kg m^{-3}, and (d) southeastward geostrophic speed in cm s^{-1} (negative values shaded) relative to the potential density surface of σ_4 = 45.87 kg m^{-3} (3440–3570 m); note the change of contour interval at the broken line. Station numbers indicated along top are for the Agulhas Retroflection Cruise (ARC) and Ajax cruise leg 1. Relative maxima are denoted by open circles, and relative minima by dots.

ternational Geophysical Year of 1959 can be used to close the region in the north. Although this third section is not synoptic with the other two, a mass balance can still be attained; there is a net northward transport of 26 Sv in the upper 1000 m through the appropriate portion of the *Atlantis* section. That section was also used by Stramma and Peterson (1989) to close the southern side of a region containing the Benguela Current, and a near mass balance was obtained when using a shallower reference layer (just above the North Atlantic Deep Water as opposed to just below in the present case). But as they pointed out, transport rates in this region are not particularly sensitive to which deep reference layer is used. An example given here is for eastward transport in the upper 1000 m between 35° and 40°S (containing the STF) from the R/V *Knorr* Ajax Cruise Leg 1 at 1°E: a reference near the bottom (deepest depths available) yields 22.2 Sv, a reference at σ_4 = 45.87 kg m^{-3} (~3500-m deep) gives 20.5 Sv, and finally from a reference near σ_2 = 36.9 kg m^{-3} (~1800-m deep) there are 19.7 Sv.

Shown in Fig. 7 is an interpretation of the flow field in the upper 1000 m within the triangular region enclosed by the *Knorr* sections. The pattern shown in the north conforms to observations of the Benguela Current made by Stramma and Peterson (1989). Although various interpretations can be made as to how the details of the field should look, there are nonetheless two important observations to be made. The first is that the transport of the SAC at and south of the STF near the prime meridian simply cannot continue east with the STF; it must for the most part turn north and complete the gyre circulation. The current that originates in western South Atlantic and flows across the basin with the STF is not a part of the Antarctic Circumpolar Current, which was also (briefly) commented on by Hart and Currie (1960). The second observation is that a small part of the circulation along the northern side of the large Agulhas ring crossed by the diagonal section flows into the Benguela Current. Gordon et al. (1987) estimated this flux as being 10 Sv and composed mainly of Indian Ocean water with some contribution from the Atlantic. Here we find it to be about 8 Sv.

4. Summary

In this paper we have looked into how the Subtropical Front gets organized in the western South Atlantic, how it is oriented from there to the other side of the Atlantic, and have investigated the current associated

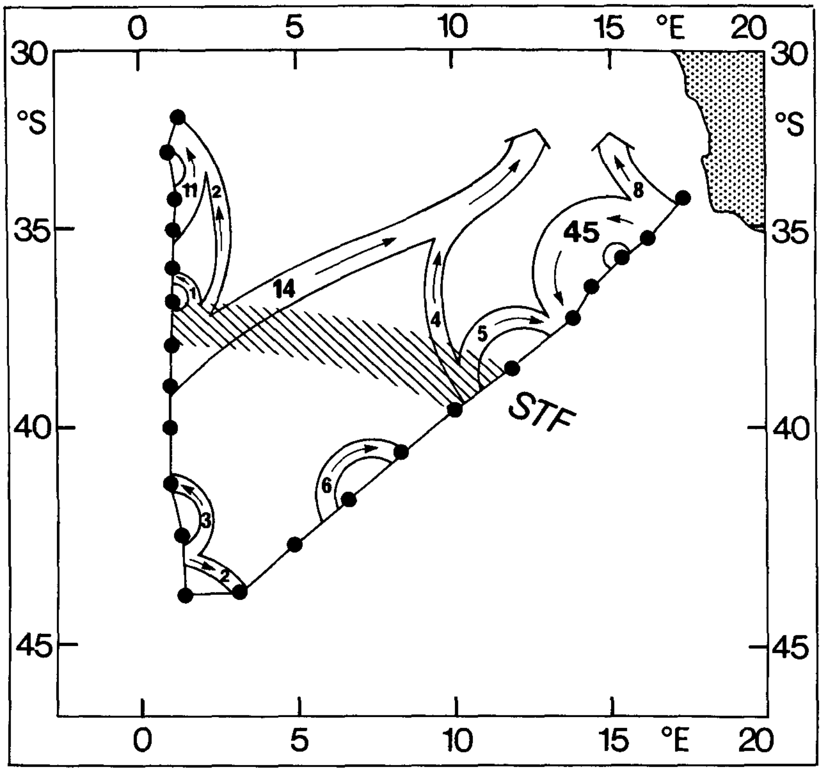

FIG. 7. Field of geostrophic volume transport (Sv) in the upper 1000 m relative to the potential density surface of σ_4 = 45.87 kg m^{-3} in the region enclosed by two sections made by the R/V *Knorr* (dots) in October and November 1983. Except coastal stations, the reference level lies in the depth range of 3350–3730 m.

with the front. By definition, the STF is the hydrographic boundary between subtropical and subpolar waters. It therefore begins where Brazil Current water flowing south along the South American continental shelf first meets subantarctic water advected north along the shelf by the Falkland (Malvinas) Current. This takes place in the Brazil–Falkland confluence zone near 55°W. But also tracable to this region is the Brazil Current front. Owing to complexities of the eddy field in the confluence zone, these two fronts are not always distinct once they first separate from each other. As the Brazil Current executes its poleward anticyclonic extension the STF undergoes an organizational phase that persists to at least 45°W. In the region just west of 40°W, however, Roden (1986) observed the two fronts to be distinct features, consistent with our findings in the same region and points farther east. From there the STF describes a course toward the east near 40°S much the same as that given by Deacon (1933, 1937, 1982).

The current associated with the STF is typically at and north of the surface front, and closes the circulation of the South Atlantic subtropical gyre in the south. South of the STF is a region of weak flow that separates the southern limb of the subtropical gyre, referred to as the South Atlantic Current, from the Antarctic Circumpolar Current. At depths of 800–1000 m, the SAC is still recognizable as an enhanced current core, so it is more than just a surface drift. In the west, after the STF and Brazil Current front are clearly apart from one another, the SAC has a volume transport that averages about 30 Sv in the upper 1000 m and can be as high as 37 Sv. Its transport diminishes to less than 15 Sv in the vicinity of southern Africa, whereupon it turns northward to feed the Benguela Current. About 8 Sv of water from the Agulhas Current joined this northward flow in November 1983. Trajectories of surface drifters north of about 40°S also show the northward turn, whereas drifters south of 40°S continued east into the Indian Ocean (Piola et al. 1987). A schematic presentation of our observations of the STF and the SAC is given in Fig. 8 (excluding those from the *Meteor* section). In cases where the current does not follow the front, the current is shown with arrows. Also shown are patterns for the Brazil Current and its recirculation (Stramma 1989; Gordon and Greengrove 1986), the Benguela Current (Stramma and Peterson 1989) and the Subantarctic and Polar fronts (Peterson and Whitworth 1989; Whitworth and Nowlin 1987; Nowlin and Klinck 1986).

As depicted in Fig. 8 and discussed in the text, there are only a few quasi-synoptic sections available which

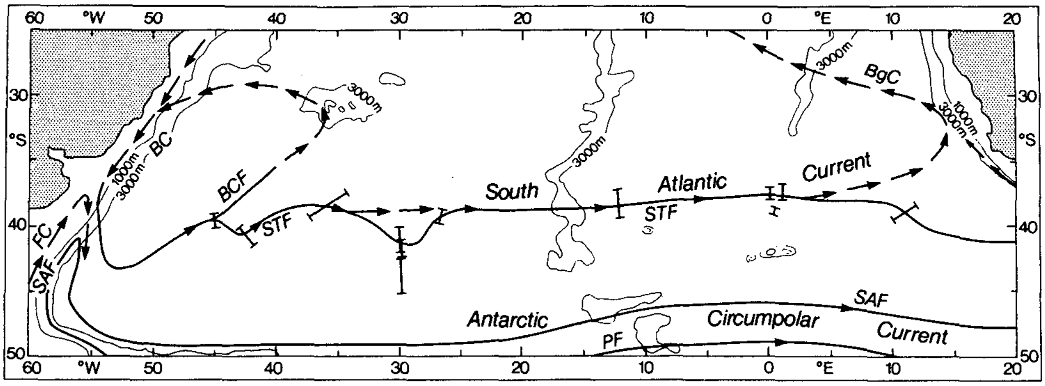

FIG. 8. Schematic illustration of midlatitude fronts (solid lines) and currents (solid lines or arrows) in the South Atlantic Ocean. Abbreviated terms are: Brazil Current (BC), Falkland Current (FC), Benguela Current (BgC), Brazil Current Front (BCF), Subantarctic Front (SAF), and Polar Front (PF). Bars denote station pairs spanning the STF as observed here.

can be used to investigate the South Atlantic Current. Many important questions concerning this current, such as those concerning its seasonal variability and possible responses to the mid-ocean ridge, await additional data. But nevertheless, it is clear that the South Atlantic Current exists, that it is a significant current, and that it closes the circulation of the South Atlantic subtropical gyre in the south.

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